Drill String Wave Modes Produced by a Working Drill Bit

James W. Rector III, Univ. of California, Berkeley

Summary

Surface geophones record two groups of arrivals resulting from drill bit impacts on a formation during drilling. One group of arrivals consists of body waves radiated into the earth. These arrivals have been documented in previous studies (Rector and Marion, 1991; Rector and Weiss, 1989; and Rector and Hardage, 1991). The second group of arrivals are 'drillstring arrivals'. They are initiated by the bit impacts, and travel up the drillstring as an extensional wave. Energy transfer between the drillstring and the adjacent formation results in seismic waves travelling into the earth, away from the drillstring. These waves can be identified in correlated drill bit wavefields.

Introduction

When recording conventional VSP data, the velocity contrast between the formation surrounding the borehole and the fluid within the borehole creates guided waves, such as Stoneley waves, that travel up and down the fluid column and the formation interface. The main differences in the characteristics of borehole wave propagation in conventional VSP and a drill bit wavefield is due to the presence of the drillstring attached to the drill bit. The partial replacement of borehole fluid with steel drillstring changes the boundary conditions of the borehole system, modifying wave propagation inside the borehole and creating a new class of arrivals, termed drillstring arrivals, that radiate from the drillstring into the earth. We draw upon real data examples to identify drillstring arrivals and we distinguish these arrivals from primary body wave arrivals emanating from the drill bit based on correlation lag and moveout with wellhead offset and bit depth.

Simple Model of Drillstring Arrivals

The drill bit impacts at the bottom of the borehole are monitored by means of a pilot sensor attached to the top of the drillstring (Rector and Marion, 1991). This pilot sensor records waves that are initiated at the drill bit and travel up and down the drillstring at a velocity near the extensional wave velocity of a steel rod (approximately 4850 m/s). Surface geophones can record energy that has been transferred from the drillstring wave into the earth at several points along the drillstring, resulting in three distinct drillstring arrivals:

1) Rig Arrivals

2) Head Wave (or Conical Wave) Arrivals

3) Drillstring Multiple Arrivals

Before discussing real data examples, we describe the travelpaths taken by these drillstring arrivals.

<u>Rig Arrivals</u>

In correlated drill-bit wavefields, one of the principal arrivals has a correlation lag and a moveout that identify it as being transferred from the drillstring to the earth via the drilling rig assembly. As shown in Figure 1, the rig arrival is modeled as entering into the rig mast through the drilling lines and traveling into the earth through the feet of the rig. An array of geophones extending away from the rig would be expected to record rig arrivals with characteristics similar to a shot gather from a source position at the rig.

<u>Head Wave Arrivals</u>

The radial displacement of the drillstring extensional wave is related to the axial displacement through Poisson's ratio for steel (approximately .29). This radial displacement imparts acoustic energy into the fluid and then into the formation. When the phase velocity of the drillstring wave is greater than the formation velocity, the energy imparted into the formation forms a wavefront with characteristics similar to head waves returning from a high-velocity, critically-refracting layer (the critically refracting layer in this case is the drillstring). Head waves were predicted by White (1965), who described them in three dimensions as conical waves.

As with energy partitioning of Stoneley waves, the impedance mismatch between the drillstring, the fluid, and the formation would be expected to produce a head wave displacement that is a small fraction of the drillstring wave displacement. However, unlike tube waves, whose amplitude decreases exponentially away from the borehole wall, the head wave amplitude decreases as the square root of the perpendicular distance form the borehole wall (White, 1965). As a result, head waves may be recorded with geophones located a long distance from the wellhead.

In the far-field of a homogeneous solid, the wavefront of the head wave makes an angle, θ_c, with respect to the borehole axis where:

$$\sin\theta_c = \frac{\alpha}{V_{ds}} \qquad (1)$$

In equation 1, α is the formation velocity and V_{ds} is the phase velocity of the drillstring wave. Near the borehole, the wavefront is defined by a modified Hankel function with a wavefront that is perpendicular to the borehole axis at the borehole. The raypaths of the head wave are depicted in Figure 1 for a formation velocity of 10,000 ft/s (3048 m/s). As shown in Figure 1, geophones near the rig record head waves that intersect the drillstring near the surface, while longer surface offsets record head waves that arrive from deeper portions of the drillstring.

Drillstring Multiple Arrivals

Energy is also transferred from the drillstring into the earth at the drill bit after traveling up the drillstring, reflecting from a change in the cross-sectional area of the drillstring, and traveling back down to the bit. Drillstring multiple arrivals were documented by Rector and Marion (1991) in the pilot sensor recording at the top of the drillstring. A Bottom Hole Assembly (BHA) multiple is radiated at the bit after reflecting from the BHA/drillpipe interface. A multiple can also be generated after reflecting from the top of the drillstring. Only a small fraction of the multiple energy traveling down to the bit is radiated into the earth. The remainder travels back up the drillstring where it can create secondary rig arrivals, secondary head wave arrivals, and higher-order drillstring multiples.

Drillstring Arrival Identification

As shown by Rector and Marion (1991), an arrival traveling from the drill bit through the earth to the surface is time-advanced in the drill-bit VSP crosscorrelation function by the traveltime from the bit to the top of the drillstring. Primary head waves from locations along the drillstring will be time-advanced by lesser amounts. For the case of a primary rig arrival, there is no time advance, and the correlation lag is equivalent to the earth traveltime.

Figure 2 shows a drill bit wavefield recorded at a bit depth of 5600 ft on a vertical well with a spread of geophone arrays extending away from the wellhead. Each array consisted of four geophones placed 25 ft apart. In addition to a primary P-wave direct arrival, four drillstring arrivals are labeled. Inspection of the wavefields shows that each of the arrivals exhibits a characteristic moveout and correlation lag.

The P-wave direct arrival has a hyperbolic moveout with offset. The hyperbolas flatten as depth increases. The BHA and drillstring multiples exhibit the same hyperbolic moveout but are delayed from the primary arrival by times T_{BHA} and T_{ds}, where:

$$T_{BHA} = \frac{2L}{V_{ds}}$$
$$T_{ds} = \frac{2Z}{V_{ds}} \qquad (2)$$

and L is the BHA length and Z is the length of the drillstring. The rig arrival in Figure 2 has nearly linear moveout with offset. The delay and moveout of this arrival is similar to the delay and moveout of the 'first break' arrival observed in seismic shot records from the area.

The head wave arrivals in Figure 2 can be distinguished from rig arrivals based on their time delay. The delay of the head wave arrival is nearly coincident with the rig arrival at the close-in offsets. At longer offsets, the head wave arrives more than 100ms earlier than the rig arrival. Since no arrival from the rig can occur before the first break time, this arrival must come from an apparent source position down the drillstring. The head wave arrival time is advanced from its earth traveltime by Z_h / V_{ds}, where Z_h is the head wave source depth.

The head wave arrival can be distinguished from point sources along the drillstring based on moveout with offset. If these arrivals were point sources, they would exhibit hyperbolic moveout like the direct arrival. Assuming a homogeneous earth, the head wave moveout, M_{hw}, is:

$$M_{hw} = \frac{\cos\theta_c}{\alpha} \qquad (3)$$

The moveout is only a function of the formation velocity adjacent to the drillstring and the inclination of the drillstring.

Moveout With Depth

Figure 3 shows a series of drill bit wavefields sampled at 30 ft intervals of bit depth and recorded with a vertical geophone array 2532 ft (772 m) from the wellhead. The data were recorded on a vertical well drilled in sediments similar to the well where the data in Figure 2 were acquired. The linear geophone array consisted of forty-eight phones spanning 300 ft. This array attenuated the short-wavelength head wave and rig arrivals, while preserving longer-wavelength P-wave direct arrivals and drillstring multiples. In addition to the arrivals labeled on Figure 2, a reflection from below the bit is also labeled in Figure 3. Each of these arrivals has a characteristic moveout as a function of bit depth.

Assuming a straight raypath, the moveout of the direct arrival with depth, M_d, is:

$$M_d = \frac{\cos\phi}{\alpha} - \frac{1}{V_{ds}} \tag{4}$$

and the moveout of a reflection, M_r, is approximately given by:

$$M_r = -\frac{\cos\phi}{\alpha} - \frac{1}{V_{ds}} \tag{5}$$

where α is the formation velocity and ϕ is the raypath takeoff angle. The corresponding moveout equations for conventional VSP would omit the term $1/V_{ds}$. Therefore, the moveout of the drill bit arrival is always less than the corresponding VSP arrival moveout, and the negative moveout of the reflection arrival is always greater than the corresponding VSP reflection moveout. The BHA multiple mimics the moveout of the direct arrival. The moveout of the drillstring multiple relative to the direct arrival moveout is $2/V_{ds}$.

Both the head wave arrival and the rig arrival exhibit zero moveout with bit depth in Figure 3. The head wave and the rig arrival are both created by radiation of the upward-traveling extensional wave. As the bit moves deeper, both the head wave arrival recorded by the geophone array and the extensional wave arrival recorded as the pilot signal at the top of the drillstring are delayed by the same amount. Therefore, the moveout of a primary head wave or rig arrival with depth is zero regardless of receiver offset, borehole deviation, or formation velocity. The depth at which the head wave arrival and the direct arrival intersect determines the radiation depth along the drillstring.

The moveout differences between the different arrivals in Figure 3 suggest that conventional VSP wavefield separation techniques can be used to extract the primary drill bit direct and reflected arrivals. Since the rig and head wave arrivals have zero moveout with depth, a filter rejecting events that appear to move along the depth axis with infinite apparent velocity (zero spatial frequency) will attenuate these events.

Conclusions

Drillstring arrivals can be identified on the basis of correlation time and moveout with depth and offset. The principal drillstring arrivals can be categorized based on their radiation position along the drillstring. Rig arrivals are radiated into the earth through the drill rig at the top of the drillstring. Drillstring multiple arrivals are radiated into the earth at the bit. Head wave arrivals are radiated into the earth along the entire length of the drillstring. For a given surface geophone offset recording a head wave arrival, the source zone along the drillstring is determined by the formation velocity adjacent to the drillstring and the inclination of the drillstring. Under some conditions, the drillstring arrivals can interfere with the primary arrivals from the bit. Conversely, the drillstring arrivals provide additional propagation paths through the earth, and could potentially be exploited to yield an improved subsurface image around the drillhole.

References

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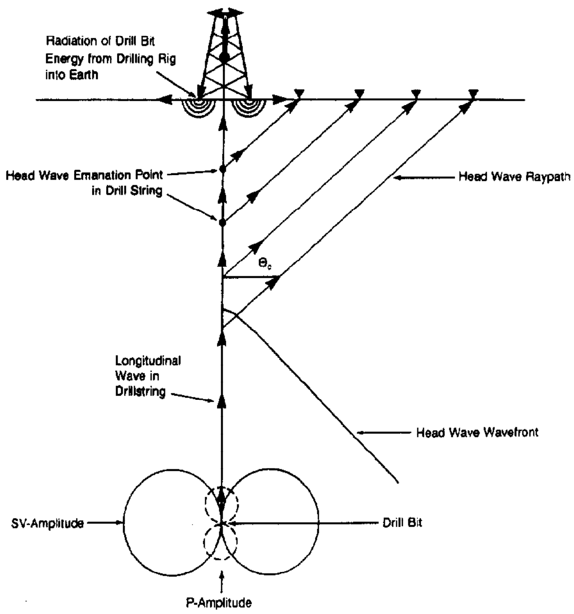

Figure 1: Diagram illustrating body wave radiation pattern of a roller-wave drill bit and †travelpaths taken by drillstring arrivals.

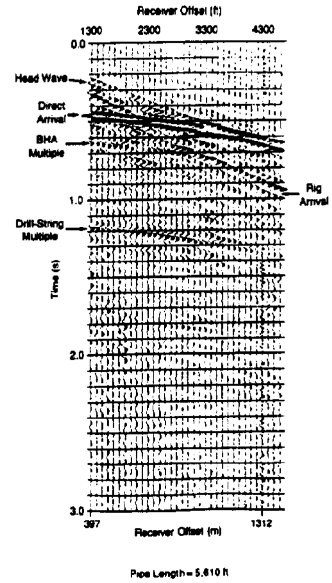

Figure 2: Correlated drill bit data from a surface geophone array

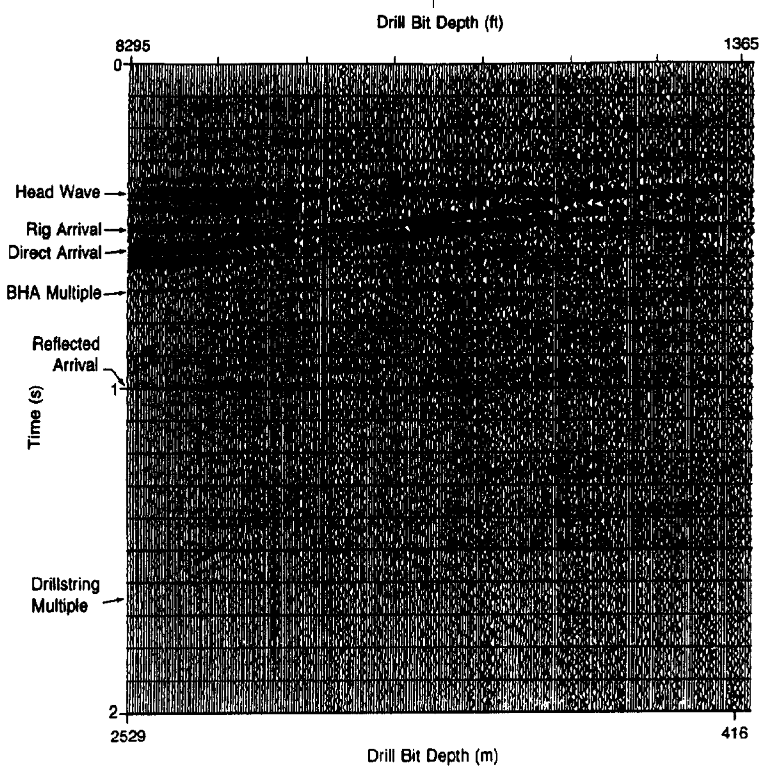

Figure 3: Correlated drill bit arrivals recorded from a single surface array.